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(54) Multiple temperature autoregulating heater.

(57) A multiple temperature autoregulating heater comprises a laminate of a conductive material, a first ferromagnetic layer on a surface of the conductive material and a second ferromagnetic layer insulated from the first layer. The layers have different Curie temperatures. A switching device is provided to connect one or the other of the layers to be energized from a constant current source. The device autoregulates in the region of the Curie temperature of the selected layer. The conductive material may be non-magnetic (copper) or a low resistivity ferromagnetic material having a Curie temperature well above the Curie temperatures of the autoregulating layers. In the latter case, a thin layer of copper or the like may be interposed between the surface and the conductive ferromagnetic material to further increase conductivity. The device may be provided with multiple ferromagnetic layers to provide multiple different autoregulating temperatures.

50 Hz – 10 KHz
P. 8, ln 22

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MULTIPLE TEMPERATURE AUTOREGULATING HEATER

The present invention relates to autoregulating electric heaters and more particularly, to an electromagnetic autoregulating electric heater that autoregulates at two or more selectable temperatures.

In the U.S. Patent No. 4,256,945 of Carter and Krumme, there is described an autoregulating electric heater having a laminated structure; one lamina of which has high magnetic permeability and high resistance and another lamina of which is non-magnetic and has a low resistance (such as copper) in electrical contact, and therefore, thermal contact with the first lamina. This structure is adapted to be connected across a constant current, a.c., source such that the layers are in a sense in parallel across the source.

Due to skin effect, the current is initially confined to the high magnetic permeability, high resistance layer so that $P = KR_1$ where P is power, K is I^2 which is a constant, and R is the effective resistance of the permeable material at high current concentrations. The dissipation of power heats the layer until it approaches its Curie temperature. The permeability of the lamina decreases towards the level of the second layer, copper for instance, at about its Curie temperature. The current is no longer confined to the high resistivity first lamina by the magnetic properties of the first lamina, and spreads into the copper layer; the resistance to the current drops materially, the power consumed, $P = KR_2$ where $R_2 << R_1$, is greatly reduced and the heating effect is reduced to a level that maintains the

device at or near the Curie temperature. The device thus thermally autoregulates over a narrow temperature range about the Curie temperature.

The current source employed in the aforesaid patent is typically a high frequency source, for instance, 8 to 20 MHz to insure that the current is confined to the thin, high resistivity, magnetic layer until the Curie temperature of the magnetic material is attained. Specifically, the maximum regulation is achieved when the thickness of the magnetic layer is of the order of one skin depth at the frequency of operation. Under these circumstances, the maximum change in effective resistance of the structure is achieved at or about the Curie temperature. This fact can be demonstrated by reference to the equation for skin depth in a monolithic, i.e., non-laminar magnetic structure: $S.D. = 5030\sqrt{\frac{\rho}{\mu f}}$ cm, where ρ is the resistivity of the material in ohm-cms, μ is magnetic permeability mu and f is frequency of the current. The field falls off in accordance with e^{-x} where x is thickness/skin depth. Accordingly, in a monolithic structure, by calculation, 63.2% of the current is confined to one skin depth in the high mu material. In the region of the Curie temperature, where $\mu = 1$, the current spreads into a region $S.D. = 5030\sqrt{\frac{\rho}{\mu f}}$ cm. If mu was originally equal to 200(200-600 being possible), the skin depth in the region at the Curie temperature increases by the square root of 200; i.e., the skin depth in the monolithic structure is now 14.14 times greater than with $\mu = 200$.

The same type of reasoning concerning the skin effect may be applied to the two layer laminar structure in the

aforesaid patent. Below the Curie temperature, the majority of the current flows in the magnetic layer when the thickness of this layer is nominally one skin depth of the material below the Curie temperature. In the region of the Curie temperature, the majority of the current now flows in the copper and the resistance drops dramatically. If the thickness of this high mu material were greater than two skin depths, the percentage change of current flowing in the high conductivity copper would be less and the resistivity change would not be as dramatic. Similarly, if the thickness of the high mu material were materially less than one skin depth, the percentage of current flowing in the high resistivity material at a temperature less than the Curie temperature would be less so that the change of resistance at the Curie temperature would again not be as dramatic. The region of 1.0 to perhaps 1.8 skin depths of high mu material is preferred.

An exact relationship for the two layer case is quite complex. The basic mathematical formulas for surface impedance from which expressions can be obtained for the ratio of the maximum resistance, R_{max}, below the Curie temperature, to the minimum resistance, R_{min}, above the Curie temperature, are given in Section 5.19, pp. 298-303 of the standard reference, "Fields and Waves in Communications Electronics," 3rd Edition, by S. Ramo, J.R. Winnery, and T. VanDuzer, published by John Wiley and Sons, New York, 1965. Although the theory described in the above reference is precise only for the case of flat layers, it is still accurate enough for all practical applications in which the

skin depth is substantially less than the radius of curvature.

Difficulty may arise in such devices when the Curie temperature is achieved due to spread of the current and/or magnetic flux into adjacent regions outside of the device, particularly if the device is located close to sensitive electrical components.

In copending patent application of Carter and Krumme, S.N. 243,777, filed March 16, 1981, a continuation-in-part application of the application from which the aforesaid patent matured, there is described a mechanism for preventing the high frequency field generated in the heated device from radiating into the regions adjacent the device. This effect is accomplished by insuring that the copper or other material of high conductivity is sufficiently thick, several skin depths at the frequency of the source, to prevent such radiation and electrical field activity. This feature is important in many applications of the device such as a soldering iron where electromagnetic fields may induce relatively large currents in sensitive circuit components which may destroy such components.

As indicated above, the magnetic field in a simple, single layer, i.e., monolithic structure, falls off as e^{-x} so that at three skin depths, the field is 4.9% of maximum, at five skin depths, it is 0.67%, and at ten skin depths, the field is .005% of maximum. For many uses, thicknesses of three skin depths are satisfactory although ten or more may be required with some highly sensitive devices in the vicinity of large heating currents.

The devices of the patent and application are

operative for their intended purposes when connected to a suitable supply, but a drawback is the cost of the high frequency power supply. Where only a very low field may be permitted to radiate from the device, the frequency of the source is preferably maintained quite high, for instance, in the megahertz region, to be able to employ copper or other non-magnetic material having reasonable thicknesses.

In accordance with the invention of co-pending application of John F. Krumme, S.N. 430,317, entitled "Auto-regulating Electrically Shielded Heater," filed on 9/30/82, a relatively low frequency constant current source may be employed as a result of fabricating the normally non-magnetic, low resistivity layer from a high permeability, high Curie temperature material. Thus, the device comprises a high permeability, high resistivity first layer adjacent the current return path and a high permeability, preferably low resistivity second layer remote from the return path; the second layer having a higher Curie temperature than the first-mentioned layer.

As used herein, the term "high magnetic permeability" refers to materials having permeabilities greater than para-magnetic materials, i.e., ferromagnetic materials, although permeabilities of 100 or more are preferred for most applications.

The theory of operation underlying the invention of the aforesaid application filed on September 30 1982 is that by using a high permeability, high Curie temperature material as the low resistivity layer, the skin depth of the current in this second layer is such as to confine the

current to a quite thin layer even at low frequencies thereby essentially insulating the outer surfaces electrically and magnetically but not thermally with a low resistivity layer of manageable thickness. The second layer is preferably formed of a low resistivity material, but this is not essential.

An example of a device employing two high mu laminae utilizes a layer of Alloy 42 having a resistivity of about 70-80 micro-ohms-cm, a permeability about 200, and a Curie temperature of approximately 300° centigrade. A second layer is formed of carbon steel having a resistivity of about 10 micro-ohms-cm, a permeability of 1000, and a Curie temperature of about 760° centigrade. The skin depths, using a 60 Hz supply are .1" for Alloy 42 and .025" for carbon steel. An example of a practical 60 Hz heater based on the present invention, may employ a coaxial heater consisting of a .25 inch diameter cylindrical or tubular copper conductor (the "return" conductor), a thin layer (perhaps .002 in thickness) of insulation, followed by the temperature sensitive magnetic alloy having a permeability of 400 and a thickness of 0.1 inch, and finally an outer jacket of steel having a permeability of 1000 and a thickness of 0.1 inch. The overall heater diameter would be a .65 inch. If the heater is used in a situation requiring 5 watts per foot of heater length for, for instance, protection of a liquid against freezing, the total length of the heater is 1000 feet, the resistance of the heater will be 1.96 ohms. The current will be 50 amperes, and the voltage at the generator end will be 140 volts at temperatures somewhat below the Curie temperature of the

temperature sensitive magnetic alloy on the inside of the outer pipe. If there were substantial changes in the electrical resistance due to variations of the thermal load, the required voltage must vary in order to maintain constant current. Either of these latter supplies provide current at costs considerably less than a constant current supply at 8-20 MHz.

The power regulation ratios (AR) in such a device; 2:1 to 4:1, are not as high as with the device of the patent with a resistivity difference of about 10:1, but the AR difference may be reduced by using materials of higher and lower resistivities for the low Curie temperature and high Curie temperature materials, respectively. Also, a high mu, relatively low resistivity material such as iron or low carbon steel may be employed to further increase the power regulation ratio.

In accordance with the invention of co-pending patent application S.N. 445,862 of John F. Krumme filed on December 1, 1982, autoregulating power ratios of 6:1 to 7:1 are attained while retaining the ability to utilize low frequency supplies without producing unacceptable levels of field radiation.

The objects of the invention are achieved by providing a region of high conductivity at the interface of the two members having high permeability as set forth in the Krumme application, S.N. 430,317, filed on September 30, 1982.

The material in the interface region may be copper, for instance, or other highly conductive material. The material may appear as a separate layer, a sandwich of

magnetic, non-magnetic and magnetic material or may be bonded to the high and/or low Curie temperature, ferromagnetic layers at the interface to provide a low resistivity, interface region.

Typical thicknesses of the sandwich construction at 1 KHz are 0.03" for both the low and high Curie temperature ferromagnetic materials, respectively, and .010 inch for the copper layer.

In operation, as the Curie temperature of the first layer is approached and its permeability rapidly decreases, the current spreads into the copper layer and into the second magnetic layer. The total resistance of the structure, due to the presence of the copper, drops dramatically providing a high autoregulating ratio. Also, most of the current is confined to the copper layer and only a small percentage penetrates into the second magnetic layer. In consequence, this latter layer need be only 3 to 5 skin depths thick to effect virtually complete shielding of the device. Thus, the object of a large autoregulating power ratio in a relatively small device using a low frequency source is achieved. By a low frequency is meant a source in the range of 50 Hz to 10,000 Hz although 50 Hz-8000 Hz is fully adequate.

With autoregulating ratios of 6:1 and 7:1, the heating variations below and above Curie temperature are quite large so that the apparatus may respond rapidly to thermal load variations and thus maintain accurate temperature regulation in a small device operating at low frequency.

In accordance with the present invention, two opposed surfaces of a laminate of conductive material are coated each with a ferromagnetic material of different Curie temperature. The term "conductive material" as used herein may refer to a highly conductive non-magnetic material such as copper or a ferromagnetic material of relatively high conductivity and a Curie temperature well above the Curie temperatures of the ferromagnetic surface coatings. In the latter case, a thin layer of copper or the like may be interposed between the surface layers and the ferromagnetic substrate to increase conductivity above the Curie temperature of the ferromagnetic layers. To complete the device, two current return paths are employed each adjacent to and insulated from a different one of the laminates of ferromagnetic material; the return path and ferromagnetic material being connected together at one end of the structure only.

A constant current source is, by means of appropriate switching arrangements, alternatively connected across one or the other of the pairs of ferromagnetic coating and its return path. Autoregulation occurs in the region of the Curie temperature of the connected ferromagnetic coating. Preferrably the conductive laminate is of sufficient thickness, 5 to 10 skin depths to prevent interaction of the ferromagnetic layers. Since each of the two surface coatings have different Curie temperatures, the apparatus autoregulates at about the Curie temperature of the surface coating connected in the circuit.

The term constant current as employed herein does not mean a current that cannot vary, but means a current that obeys the following formula:

$$\frac{\Delta I}{I} < -1/2 \frac{\Delta R}{R} \quad (1)$$

Specifically, in order to autoregulate, the power delivered to the load when the heater exceeds Curie temperature, must be less than the power delivered to the load below Curie temperature. If the current is held invariable, then the best autoregulating ratio is achieved short of controlling the power supply to reduce current. So long, however, as the current is reduced sufficiently to reduce heating, autoregulation is achieved. Thus, when large autoregulating ratios are not required, constraints on the degree of current control may be relaxed thus reducing the cost of the power supply.

The above equation is derived by analyzing the equation:

$P = (I + \Delta I)^2 (R + \Delta R)$ where P is power,

Differentiating P with respect to R

$$\frac{dP}{dR} = I^2 + 2RI\left(\frac{dI}{dR}\right) \ldots$$

and to satisfy the requirements for autoregulation $\frac{dP}{dR} < 0$. Thus, $I^2 + 2RI\left(\frac{dI}{dR}\right) < 0 \ldots$ which reduces to Equation 1 above.

A device that autoregulates at more than two temperatures is also disclosed by providing insulating spaces between pairs of autoregulating devices. Specifically, the concentration of current in a conductor due to skin effect is on the surface of the conductor adjacent the

current return path. If three layers separated by two conductive paths are employed in an attempt to provide a device with three (or more) autoregulating temperatures, a conductive path is provided along both surfaces of the ferromagnetic material, and the current will flow at all times predominantly in the conductive medium and autoregulation is defeated. By providing a non-conductive space between certain of the layers, three or more temperatures may be achieved. Since, however, the basic concept behind devices of this general character is to heat a given medium, insulation of part of the heater from another part may defeat the basic purpose of the device unless the layers are separated by a heat conducting electrical insulator or the material to be heated lies in the space between the two parts of the heater. Appropriate matching is employed to maintain the current return path at the appropriate location related to the selected ferromagnetic surface layer.

It is an object of the present invention to provide a multi-temperature autoregulating heater.

Another object of the present invention is to provide a multi-temperature autoregulating heater in which the desired temperature may be selected at will.

The above and still further objects, features and advantages of the present invention will become apparent upon consideration of the following detailed description of one specific embodiment thereof, especially when taken in conjunction with the accompanying drawing, wherein:

Fig. 1 is a partial diagrammatic and partial electrical schematic diagram of one embodiment of a dual temperature heater of the present invention;

Fig. 2 is a partial diagrammatic and partial electrical schematic diagram of a second embodiment of a dual temperature heater of the present invention;

Fig. 3 is a partial diagrammatic and partial schematic diagram of a triple temperature heater of the present invention; and

Fig. 4 is a variation of the embodiment of Fig. 3.

Referring now specifically to Fig. 1 of the accompanying drawings, there is provided a dual temperature heater having a substrate or lamina 1 of conductive material coated on its top and bottom surfaces as illustrated in Fig. 1, with layers 3 and 5, respectively, of ferromagnetic materials of different Curie temperatures. Layers 3 and 5 are provided with insulating layers 2 and 4 located between layers 3 and 5 and current return conductors 6 and 8, respectively. A constant current source 7, has its two terminals connected to movable contacts 9 and 10 of a double pole double throw switch 11. The movable contacts 9 and 17 are switchable between stationary contacts 13 and 15, on the one hand, and contacts 19 and 21, on the other. Contacts 13 and 14 are connected respectively to ferromagnetic layer 5 and conductive layer 8. Contacts 19 and 21 are connected to layers 6 and 3, respectively. The layers 1, 6 and 8 are all connected together via a lead 10 at the end of the device remote from the connection of the source 7 to the structure.

In operation, if heating to the temperature of the layer 3 is desired, the contacts 9 and 17 engage, respectively, contacts 19 and 21. Initially, due to skin effect resulting from appropriate selection of the depth of the layer 3, the mu and resistivity of the layer 3 and the frequency of the source, over 80% of the current may be confined to the layer 3. The resultant heating quickly raises the temperature of the device to about the Curie temperature of the layer 3. At this time, the mu of the layer falls to about one, and the current spreads into the conductive layer 1. The I_2R losses decrease due to a large decrease in the value of R and the temperature falls below the Curie temperature of the layer 3, the heating rate increases and the cycle repeats to maintain temperature at the desired level.

If it is wished to select the temperature determined by layer 5, the switch 11 is activated to engage contacts 13 and 15. The cycle described above is repeated with temperature maintained at a temperature determined by the material of layer 5.

A table of some of the more typical ferromagnetic materials and associated Curie temperatures and other parameters as follows:

TABLE I

MATERIAL	APPROX. CURIE TEMPERATURE	ρ	EFFECTIVE PERMEABILITY
30% Ni Bal Fe	100°C	80×10^{-6}	100-300
36% Ni Bal Fe	279°C	82×10^{-6}	
42% Ni Bal Fe	325°C	71×10^{-6}	200-600
46% Ni Bal Fe	460°C	46×10^{-6}	
52% Ni Bal Fe	565°C	43×10^{-6}	
80% Ni Bal Fe	460°C	58×10^{-6}	400-1000
Kovar	435°C	49×10^{-6}	
Low Carbon Steel	760°C	10×10^{-6}	1000
Cobalt	1120°C	9.8×10^{-6}	1000
Nickel	353°C	6.8×10^{-6}	500

The material of the layer 1 may be copper or the like in which case maximum autoregulation ratio is achieved. It is preferable, though not essential in many cases, that the layer 1 be 5 to 10 skin depths thick to prevent interaction of the two magnetic layers.

As previously indicated, the layer 1 may also be a relatively high conductivity ferromagnetic material having a Curie temperature well above those of layers 3 and 5. The autoregulation ratio of such a device is not as high as with copper, but the thickness of the layer 1 may be less due to the shielding effect of the magnetic material of the layer 1.

In another alternative, the improvement disclosed in Application S.N. 445,862 may be employed. Referring

specifically to the end view of such a device as viewed in Fig. 2 of the accompanying drawings, the components common to Fig. 1 carry the same reference numerals but with primes added. In this embodiment of the invention, the layer 1, as well as the layers 3 and 5, is ferromagnetic, and a thin layer of copper or the like is disposed between layer 1 and the layers 3 and 5. Specifically, thin conductive layers 23 and 25 are located between layer 1 and layers 3 and 5, respectively.

The result is a shielded device that is thinner than the structure of Fig. 1 and where performance is, for most purposes., as effective as that of Fig. 1.

Referring now specifically to Fig. 3 of the accompanying drawings, there is illustrated a dual temperature heater patterned after the device of Fig. 5 of the aforesaid Carter et al patent.

A single current return conductor 27 of rectangular cross-section is surrounded, in the order stated, by a heat conductive, electrically insulating layer 29, for instance, of beryllium oxide, a ferromagnetic layer 31, a layer 33 that is conductive relative to layer 31, a second thermally conductive, electrically insulating layer 35, a second ferromagnetic layer 37, and a relatively conductive layer 39. Ferromagnetic layers 31 and 37 have different Curie temperatures and layers 33 and 39 may be non-magnetic conductors or ferromagnetic materials as described relative to Fig. 2.

In this embodiment, the device is in a shielded configuration in that by choosing an appropriate thickness

of the layer 39, generation of magnetic fields external to the apparatus may be eliminated. Thus, the device is not limited in the location of its applicability and may be wrapped around pipes to prevent freezing, used in diesel fuel heaters or any other location where dual heat may be desirable, such as surgical scalpels.

The entire device may be coated with beryllium oxide so that it is electrically but not thermally insulated from its environment.

The device is completed by connecting the ferromagnetic layers 31 and 37 together and to the conductor 27 via leads 32, 38 and 28. A source 41 has one end connected via lead 42 connected to return conductor 27 and the other end connected to the center contact 44 of a single pole double throw switch 43. A contact 48 is connected to layer 31 and a second contact 50 is connected to layer 37. Thus, by engaging contact 48 or contact 50, the autoregulating temperature of the device may be selected from two different temperatures.

It should be noted that by making ferromagnetic layers 31 and 37 equal to 5 to 10 skin depths thick, when the layers are above their Curie temperature, the layers 33 and 39 may be eliminated since interaction between layers 31 and 37 would be obviated and the layer 37 would be thick enough to prevent radiation even when the layers become non-magnetic. Such a device would not have very good autoregulation but would be sufficient in certain areas of use.

Referring now specifically to Fig. 4 of the accompanying drawings, there is illustrated a cylindrical

version of the device of Fig. 3. The elements of Fig. 4 corresponding to those of Fig. 3 bear the same reference numerals with primes.

The device of Fig. 4 is a thru temperature device having added layers such as layer 45 of insulation, layer 47 of a ferromagnetic material of a third Curie temperature and a final copper (shielding) layer 49. As in the apparatus of Fig. 2, the shielding layers 33^1, 39^1, and 49 may be eliminated by making the ferromagnetic layers 5 to 10 skin depths thick.

The device is provided with a source 41^1 and a single pole triple through switch 51 having stationary contacts 52, 54 and 56 connected to layer 31^1, 37^1 and 47, respectively, so that any one of the three layers and its associated Curie temperature may be selected. Of course, any number of layers, within reason, may be added to achieve even more temperatures.

It should be noted that the insulating layer 29 of Fig. 3 has been eliminated to provide a gap between return conductor 27^1 and ferromagnetic layer 31^1. This gap insulates such members from one another and may be employed to heat fluids; air, gas, water, or other liquid, for a variety of purposes. Any one of the insulating layers may be removed to accept fluid and in fact, three different fluids may be heated simultaneously to three different temperatures. Spiders of insulating material may be used to maintain separation between the layers.

If a conductive liquid is to be heated, the liquid may constitute the current return path and replace the

copper rod 27^1. Alternatively, the conductive liquid may replace any one of the copper layers 33^1, 39^1, or others as layers are added. Preferably, for purposes of heat transfer, the conductive liquid should be centrally located in the device.

As indicated by Figs. 3 and 4, the devices may be cylindrical or flat, may be a solid stack using beryllium copper, or the like, separators or a hollow stack or cylinder using air gap separation.

The switches employed may be mechanical, electromechanical or electronic and if either of the latter two lend themselves for use with automatic process controllers.

I CLAIM:

1. A multi-temperature autoregulating heater structure comprising:

a conductive substrate providing at least a first surface,

a first ferromagnetic layer on said first surface and electrically insulated therefrom,

at least a second ferromagnetic layer electrically insulated from said first ferromagnetic layer and having a Curie temperature different from the Curie temperature of said first ferromagnetic layer, and

means permitting of selective excitation of either one or the other of said ferromagnetic layers with alternating current.

2. The apparatus according to claim 1 wherein said conductive substrate has an elongated dimension and said ferromagnetic layers surround said conductive substrate along its elongated dimension.

3. The apparatus according to claim 1 wherein said members are electrically insulated from another by a heat conducting, electrically insulating material.

4. The apparatus according to claim 1 wherein said members are insulated from one another by an air gap.

5. The apparatus according to claim 1 wherein said first surface is a continuous surface encompassing said substrate and wherein said first ferromagnetic layer has a surface surrounding said surface of said substrate and

wherein said second ferromagnetic layer surrounds said surface of said first ferromagnetic layer,

a source of a.c. constant current, and

means connecting one terminal of said source to said conductive substrate and the other terminal of said source selectively to one or the other of said ferromagnetic layers, and

means connecting said substrate and said layers together electrically at a location remote from connection of said structure.

6. The apparatus according to claim 5 wherein said substrate and said layers are rectangular.

7. The apparatus according to claim 5 wherein said substrate and said layers are cylindrical.

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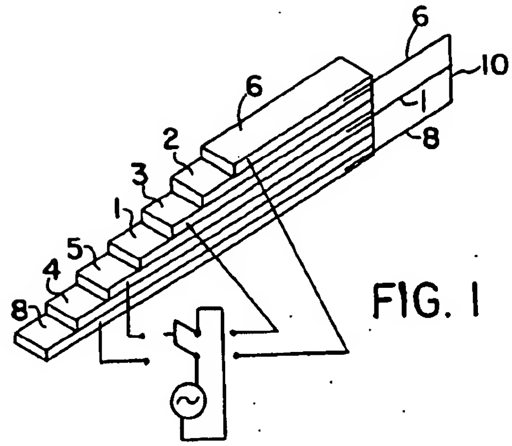

FIG. 1

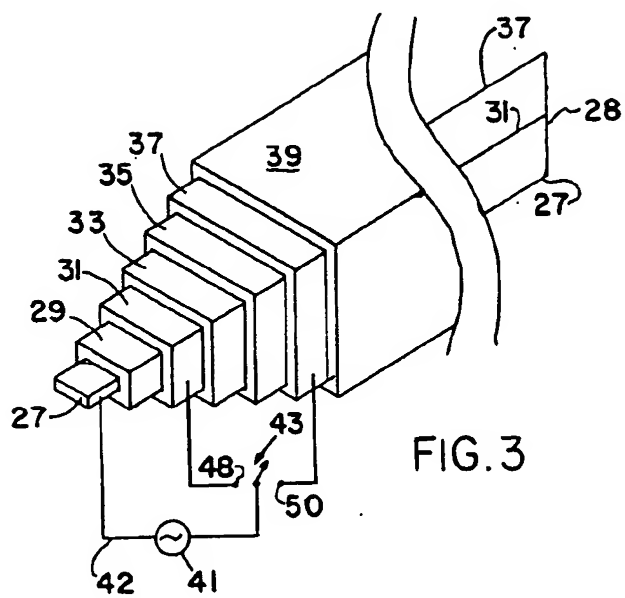

FIG. 3

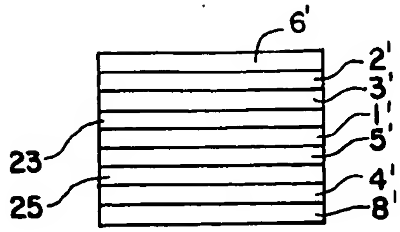

FIG. 2

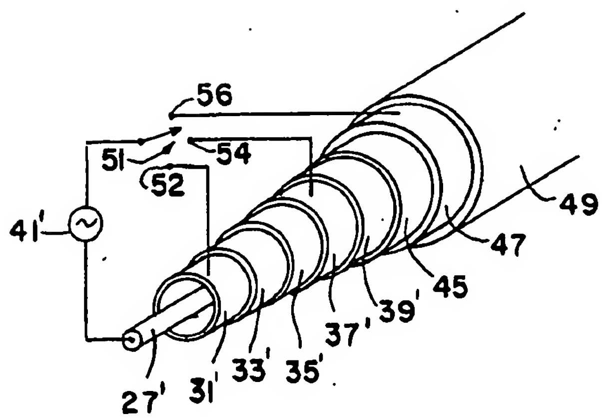

FIG. 4